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Environmental benefit of utilizing bamboo material based on life cycle assessment

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ABSTRACT

This study focuses on the production chains that produce plybamboo for use. The production chains were investigated using a life cycle assessment (LCA) approach, which takes into account all of the input and output flows occurring along the production chain. The results show that the major processing type of plybamboo production is mechanical processing. The characterization of various materials demonstrates that bleached glue-laminated bamboo boards exert the greatest potential environmental impact in terms of power consumption during the three-layer lamination process; in particular, the category with the highest environmental impact is respiratory inorganics. Therefore, energy consumption and productivity are the key factors of the potential environmental impact. The comparison of the two treatment types revealed that the bleached glue-laminated bamboo boards have a lower environmental impact in all four categories than their heat-treated counterparts. The impact of the processing mainly originates from the steps of hot pressing, drying and using chemicals. The comparative results show that plybamboo has a low environmental impact, but the impact is higher than that of concrete. Concerning the carbon storage of plybamboo, using plybamboo has environmental benefits in the impact categories of climate change and global warming. Although plybamboo has a low impact in the impact categories of climate change and global warming, it has a high impact in other impact categories. Therefore, policy makers should consider the highest impact of the aforementioned processing steps and should use energy-saving and high productivity equipment to reduce the environmental impact.

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1. Introduction

Bamboo is found in diverse climates from tropical to frigid zones. The worldwide distribution of bamboo ranges from 51°N to 47°S while the tropics boast the most abundant bamboo resources in the world. In particular, bamboo forests cover an area over 1.8×10^9 ha in East and South Asia, accounting for more than 80% of the total land area of bamboo forests worldwide (Scurlock et al., 2000). The bamboo forest area in Asia has increased by 10% in the past 15 years, and China is planning to continue its expansion of bamboo forests in upcoming years. A study estimated that carbon stocks in bamboo stands in China will increase from 727.08 Tg C in 2010 to 1017.54 Tg C in 2050, a 40% increase over a 40-year span (Chen et al., 2009). The bamboo systems planted on sloping farmland also have positive effects on water conservation and soil erosion control (Lu et al., 2018). These results show that bamboo forestation contributes to substantial carbon storage, mitigating the effects of climate change to some extent.

Bamboo forests in Taiwan cover an area of 175,638 ha with approximately 18 genera, 58 species, 4 varieties, and 11 cultivars. Among native bamboo species, *Dendrocalamus latiflorus* occupies 90,865 ha (51.7% of the total bamboo area in Taiwan); however, only 14,911 ha is purely *D. latiflorus*, and the rest is mixed forests. *Phyllostachys makinoi* covers 43,774 ha (24.92%); *Bambusa stenostachya* occupies 30,658 ha (17.5%, of which 17,280 ha is purely *B. stenostachya* with the rest in mixed forests); *Bambusa oldhamii* occupies 4459 ha (2.5%); and *Phyllostachys edulis* covers 3296 ha (1.9%). According to the 2016 report published by the Forestry Bureau of the Council of Agriculture, bamboo forests in the Taiwan–Fuchien Area occupy 183,330 ha, accounting for 8.34% of the total forest area.

Bamboo resources are used extensively in Taiwan. The primary products of *P. makinoi* and *P. edulis* are building materials, and their secondary products are edible bamboo shoots. Conversely, the

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primary products of *D. latiflorus* and *B. oldhamii* are bamboo shoots, and their secondary products are building materials. The primary products of *B. stenostachya* and *Bambusa dolichoclada Hayata* are building materials, whereas their secondary products include shelter forest plantations for sand dune stabilization. Increased labor costs and substitutes for bamboo building materials (e.g., plastics) have contributed to the decline of bamboo resource production in Taiwan. According to statistical reports in 2004, fewer than 100 bamboo factories in Taiwan were engaging in small-scale production because most factories have been relocated to China and South Asia due to lower costs. Consequently, both bamboo production and bamboo-related studies in Taiwan have declined because of decreased bamboo export (Lin, 2011). Therefore, inadequate bamboo forest management has led to abandoned and decaying bamboo, substantially decreasing the disaster prevention function of bamboo forests and wasting renewable biological resources. However, the interactions between problems such as environmental protection, climate change, and energy supply in recent years have drawn worldwide attention to environmentally friendly, fast-growing bamboo resources and a renaissance of bamboo building materials. This trend has inspired Taiwanese industries, government, and academia to revisit the rich bamboo resources in Taiwan.

Chen et al. (2009) found that the average aboveground and underground biomasses of *P. makinoi* in the Shihmen Reservoir Watershed Area were 56.48 ± 14.32 ton ha^{-1} and 168.10 ± 23.98 ton ha^{-1}, respectively. Sun et al. (2013) reported that the intensively and extensively managed *Phyllostachys pubescens* forests in Central Taiwan had aboveground biomasses of 62.0–124.3 Mg ha^{-1} and 38.6–47.1 Mg ha^{-1}, respectively. The carbon storage function inspires greater afforestation and tendering functions of forestry management. However, the land area on Earth is limited, and countermeasures against global warming should focus on reducing CO_2 emissions. Timber exhibits benefits such as energy conservation, carbon storage, and substituting petrochemical fuels (Wang and Tu, 2007).

Bamboo materials are advantageous for (1) energy conservation and the reduction of CO_2 emissions, (2) carbon storage, and (3) biochemical fuel substitution (Van der Lugt et al., 2008). Bamboo also exhibits characteristics such as fast growth and a short rotation age. Bamboo has a greater accretion rate than timber and can be logged in 3–5 years. In addition, bamboo harvesting is more accepted by the general public than timber harvesting. Bamboo resources have applications in architecture, handicrafts, and cuisine. Architectural uses of bamboo include furniture and appliances, and handicrafts use bamboo in weaving or as plybamboo. In horticulture, bamboo is widely used because of its elegant shape and fast growth. Furthermore, bamboo shoots are edible and delicious, and they can be canned or processed into *menma* (dried bamboo). Therefore, as logging bans become increasingly common worldwide, the utilization of bamboo forests not only ensures the sustainability of the natural ecological environment but also creates additional value for bamboo resources.

Natural resources are defined as naturally generated substances and energy that humans can utilize, and they provide the material basis for human survival. However, global population growth has increased resource consumption, and resource overconsumption has caused the following three environmental problems: depletion of resources, deterioration of ecosystems, and deterioration of human health. Van der Lugt et al. (2008) argued that the sources of environmental impacts can be traced back to each phase of the life cycle of a product, and most of these environmental impacts originate during the manufacturing phases, including the raw material supplying and processing phases. To mitigate these problems, renewable resources are actively being developed worldwide. Moreover, in addition to raw materials, renewable resources can be used for food production and energy generation. Consequently, the problem of limited arable land availability has led to the tradeoff problem of arable land usage for raw material supply, food production, and energy generation. For example, when arable land is used to produce bioethanol, crop production decreases, thereby increasing global food prices and affecting standards of living (Worldbank, 2008).

Bamboo is regarded as a potential replacement for hardwood, and it exhibits a high tensile strength of 3.59×10^8 N/m^2, which is comparable with steel. Since the 1990s, bamboo has been industrially processed into products with high additional value such as plybamboo, bamboo mat boards, and strand woven bamboos. These products can be used as building materials such as floor tiles and wall panels (Anwar et al., 2011). Bahari and Krause (2016) utilized the Malaysian bamboo for thermoplastic composites to reduce the demand of plastics and the environmental impact associated with their production and disposal. These results indicated that the use of bamboo not only serve as an alternative for wood-polymer composites, but also expand the commercial utilization of bamboo and development of greener and cleaner products. Therefore, given the destruction of forest resources and the increasing demand for wooden materials, these properties render bamboo a suitable replacement for hardwood.

Restrepo et al. (2016) used energy management tools and LCA to evaluate the energy and carbon footprint analysis in the manufacturing process of bamboo boards in Colombia. The process of manufacturing bamboo boards requires a specific number of subprocesses and demands a considerable amount of raw materials. The results indicated that approximately 70% of the raw material is converted into bamboo waste, and 117 kg of $CO_{2\text{-eq}}$ are not released during the manufacturing of each board.

Agyekum et al. (2017) assessed the environmental and social impact of bicycle frames made from wild Ghanaian bamboo, and the LCA results were compared with an aluminum frame and a steel frame. The results show that the overall environmental impact of bamboo bicycle frames is approximately 50% less than aluminum and 30% less than steel bicycle frames. However, the provision of safety gear for harvesting operations and supervision was inadequate.

Zea Escamilla and Habert (2014) used LCA to evaluate the environmental impacts of five processing methods for bamboo building materials. Their results revealed that the extent of the environmental impact depends on the degree of processing, with bamboo materials that require minimal processing exhibiting a low environmental impact. In addition, the processing of bamboo materials exerts a notably lower environmental effect on the ecosystem than on other aspects of the environment. The environmental impact of little-processed bamboo materials is mainly attributed to the natural gas used during drying processes. For highly processed bamboo materials, the production process requires treatments such as sawing, cutting, and hot pressing, and the power consumption during processing accounts for more than 50% of the environmental impact of bamboo building materials. Therefore, the environmental impact of highly processed bamboo materials is mainly attributed to electricity consumption. To mitigate these environmental impacts, the energy structure should be improved (e.g., the proportion of coal-based energy should be reduced). However, the species of bamboo and harvesting practices do not make a significant contribution to the overall environmental impact of bamboo-based construction materials. Zea Escamilla and Habert (2014) also recommended that future studies on this topic explore aspects such as resource acquisition, power supply, heat source supply, and logistics.

Vogtländer et al. (2010) investigated the environmental impacts of imported bamboo materials in Western Europe using the eco-cost approach. The results revealed that importing unprocessed bamboo stems resulted in a higher environmental impact than using locally produced timber and steel materials because of the impact of transporting the bamboo materials, thus reducing their excellent environmental effect. However, bamboo materials generate lower environmental impacts if they are used in China, where they are native. In addition, imported bamboo materials, regardless of whether they are processed before shipping, have a lower environmental impact than do broadleaf hardwoods produced in the tropics. Therefore, Vogtländer et al. (2010) concluded that imported bamboo materials have lower environmental impacts than tropical timbers certified by the Forest Stewardship Council, and the usage of domestic bamboo materials is more environmentally friendly than importing.

Li et al. (2016) used LCA to assess the environmental impacts during the production of glue-laminated bamboo, which was reported to exhibit advantages such as dimensional stability, high hardness, wear resistance, and environmental friendliness. Therefore, as a type of sustainable, green material, glue-laminated bamboo can be examined through LCA to comprehensively analyze its environmental impacts during production. Li et al. (2016) found that the environmental impacts, such as acidification and ozone layer depletion, are mainly attributed to the urea-formaldehyde (UF) used during the gluing process. In addition, the environmental impacts incurred by treatments such as carbonization, drying, and hot pressing are mainly attributed to power consumption.

Also known as bamboo plywood, plybamboo is a type of veneer comprising sliced bamboo stripes with identical length and width, and it is manufactured by gluing and pressing. Plybamboo exhibits advantages such as being a biological material and having strong mechanical strength, high dimensional stability, elegant grain, and subdued colors. Plybamboo is applicable to handicrafts, furniture, and building materials. In Taiwan, sales of all forms of bamboo goods currently reach $100 m, with exports increasing alongside domestic sales. The present study used LCA to examine the environmental impacts of plybamboo processing. The energy consumption (the electricity and fuel consumption of each processing equipment) of the plybamboo processing from Moso bamboo was investigated at the bamboo processing plant. The environmental impacts of bleached glue-laminated bamboo boards and heat-treated glue-laminated boards were evaluated. Additionally, the greenhouse gas emissions and environmental impacts of glue-laminated bamboo were also compared with other materials (i.e., plywood, steel, concrete, aluminum, and polyvinyl chloride).

2. Methods

A wide range of bamboo products can be made from the bamboo processing plant. Plybamboo has the advantages of being a natural material and having high mechanical strength, high dimensional stability, beautiful wood and a soft color, and it can be applied to handicrafts, furniture and building materials. In this study, Moso bamboo was cut into a uniform width, and then glue technology was used to suppress the plywood. The surface of Moso bamboo is relatively smooth, and its section is relatively low. Additionally, it has a very thick layer. Thus, Moso bamboo was chosen as the best raw material for plybamboo in Taiwan and China. Using Makino bamboo or Ma bamboo as raw materials for plybamboo would require greater energy consumption. Moso bamboo can be a substitute for wood, but its texture is not the same as wood because wood has a tree ring, whereas bamboo is straight, only a little deeper in the color of the section.

The bamboo processing plant was located in Zhushan Township, Nantou County, Taiwan. The maintenance and end-of-life was not considered in this study. This study classified the data required to assess the environmental impacts of plybamboo based on its life cycle by considering the power consumption of each processing phase (i.e., the electricity and fuel consumption of the processing equipment) (Vogtländer et al., 2010). According to the life cycle stage, the electricity and fuel consumption of each piece of processing equipment for plybamboo processing with Moso bamboo was investigated and recorded. The size of a 2440 × 1220 × 20 mm plate was used as a functional unit (Function unit, FU). This study used the inventory data of the built-in database (Ecoinvent) of SimaPro 8.2 LCA software and then modified them to reflect the actual situation in Taiwan. The life cycle assessment method (SimaPro 8.2 and IMPACT 2002 + v2.12) was used to analyze the environmental impact of the plybamboo processing with Moso bamboo. IMPACT 2002 + is one of the most widely used impact assessment methods in LCA. This method analyzes four different types of damage: human health, ecosystem quality, climate change, and resources, and the standard units for all categories are point (Pt) or millipoint (mPt) (Chang et al., 2017). The average power consumption of the processing machines is shown in Table 1. The average resource and power consumption of each processing phase from plybamboo processing is shown in Table 2. The important statements for each stage of plybamboo processing inventory analysis from Moso bamboo are shown in the supplementary material. The system boundaries of the plybamboo processing are shown in Fig. 1.

3. Results and discussions

3.1. Evaluation of environmental impacts of bleached glue-laminate bamboo boards

Glue-laminated bamboo boards vary in size and in the number of layers, and the treatment of bamboo materials can involve either bleaching or heat treatment, which results in separate environmental impacts. Fig. 2(a) illustrates the characteristics of bleached glue-laminated bamboo boards, demonstrating the environmental impacts of each life cycle phase.

H_2O_2 usage contributed the greatest effect in terms of carcinogenic toxicity, with its effects of sterilization, corrosion resistance, and bleaching being widely applied in bamboo processing; excessive H_2O_2 intake may lead to symptoms such as nausea, vomiting, abdominal distension, or diarrhea or even peptic ulcers and mucositis. Because a prolonged intake of H_2O_2 results in a higher risk of gastrointestinal cancer, H_2O_2 exhibited a substantial

Table 1
Power consumption of processing machines.

Machine type	Power (kW)
Circular saw	4.00
Battering ram	3.73
Strip planing machine	2.98
Boiler	10.00
Heat treatment furnace	1.50
Drying kiln	16.16
Fine planing machine	2.984
Heat press	46.19
Angle grinder	7.46
Saw blade for sizing	4.60
Polishing grinder	18.40
Dust-collecting device	22.38

Source: compiled in this study.

Table 2
Resource and power consumption of each processing phase.

Process	Volume	Unit
Logging	0.224	l/FU
Skidding	806	tkm/FU
Circular saw (splitting)	0.38	kWh/FU
Battering ram (slicing)	0.93	kWh/FU
Initial planing	1.46	kWh/FU
H_2O_2 addition	4.16	kWh/FU
Bleaching	2.25	kWh/FU
Heat treatment	3.68	kWh/FU
Drying after bleaching	10.1	kWh/FU
Drying after heat treatment	23.6	kWh/FU
Fine planing	0.87	kWh/FU
Hot pressing of single veneer	9.24	kWh/FU
UF resin for single veneer	894	g/FU
Initial grinding	0.16	kWh/FU
Hot pressing of glue-laminated board	13.86	kWh/FU
UF resin for glue-laminated board	953.6	g/FU
Sizing	0.24	kWh/FU
Final polishing	0.22	kWh/FU
Dust collecting	3.8	kWh/FU

Source: compiled in this study.

environmental impact in this category. The pollution generated by the lumber mill also exerted substantial environmental impacts through photochemical oxidation and mineral exploration. Moreover, the UF resin may potentially release free formaldehyde in every processing phase because of the constant effects of temperature, moisture, and lighting. Both the released free formaldehyde and the power consumption exhibited substantial hazardous environmental impacts. Therefore, UF resin usage contributed a remarkable proportion to categories such as non-carcinogenic toxicity, ozone layer depletion, respiratory inorganics, terrestrial acidification, terrestrial nitrification, and mineral exploration. During the hot pressing process of glue-laminated bamboo boards, the high power consumption of the heat press exhibited substantial environmental impacts in categories such as respiratory inorganics, ionizing radiation, aquatic ecotoxicity, terrestrial ecotoxicity, and aquatic acidification. The glue-laminated bamboo boards comprised biological materials with approximately 50% carbon; therefore, the usage of bamboo materials is equivalent to carbon storage in an organic form. Although the raw material inputs and power consumption during the production process resulted in some extent of accumulated environmental impacts, the carbon storage function of bamboo materials exhibited environmentally friendly effects that can offset the effects of production processes on global warming.

Fig. 2(b) compares the environmental impacts of each processing phase of bleached glue-laminated bamboo boards through individual scores. The four processing steps generating the most environmental impact, in descending order, were hot pressing for three-layer lamination, drying, hot pressing for single-layer lamination, and H_2O_2 usage. The environmental impacts generated by three-layer lamination were mostly attributed to the substantial power consumption incurred by high-frequency heating (as high as 35 kW). To mitigate the environmental impact during this processing phase, heating equipment improvements would be required. The major environmental impacts of the three-layer lamination, drying, and single-layer lamination phases involved respiratory inorganics, global warming, and nonrenewable energy, all of which are associated with power consumption. Therefore, the environmental impacts of the energy structure in Taiwan mostly result from these three categories.

Table 3 lists the assessment results for the endpoint impact indicator of the bleached glue-laminated boards. This indicator can be used to identify the hazards in each processing phase that are detrimental to the environment. The results indicate that the processing of glued-laminated bamboo boards exhibits high environmental impacts in hazards such as human health, climate change, and the depletion of resources, particularly during drying, hot pressing, and phases involving H_2O_2. The major source of these environmental impacts is power consumption, as caused by the energy structure in Taiwan, 78.7% of which is nonrenewable thermal power from coal, fuel oil, and natural gas (Bureau of Energy, 2014). In addition, thermal power contributes to these hazards by emitting substantial pollutants such as nitrogen oxide, CO_2, sulfur oxide, and particulates (<2.5 μm). However, because bamboo materials have carbon storage functions, they alleviate the impact of climate change and thus offset the environmental impacts caused by the processing phases, resulting in a reduced overall environmental impact. In summary, to mitigate the environmental impacts induced by the manufacturing process of bleached glue-laminated bamboo boards, the hazardous processing phases should be addressed first through measures such as using equipment that consumes less power and applying more environmentally friendly chemicals.

3.2. Evaluation of environmental impacts of heat-treated glued-laminate boards

Fig. 3(a) illustrates the characteristics of heat-treated glued-

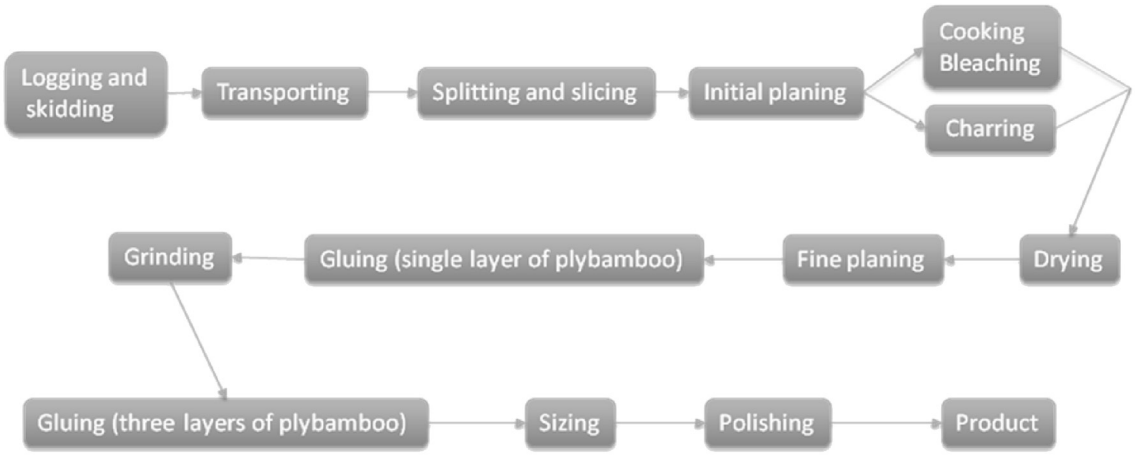

Fig. 1. System boundaries of plybamboo processing from Moso bamboo.

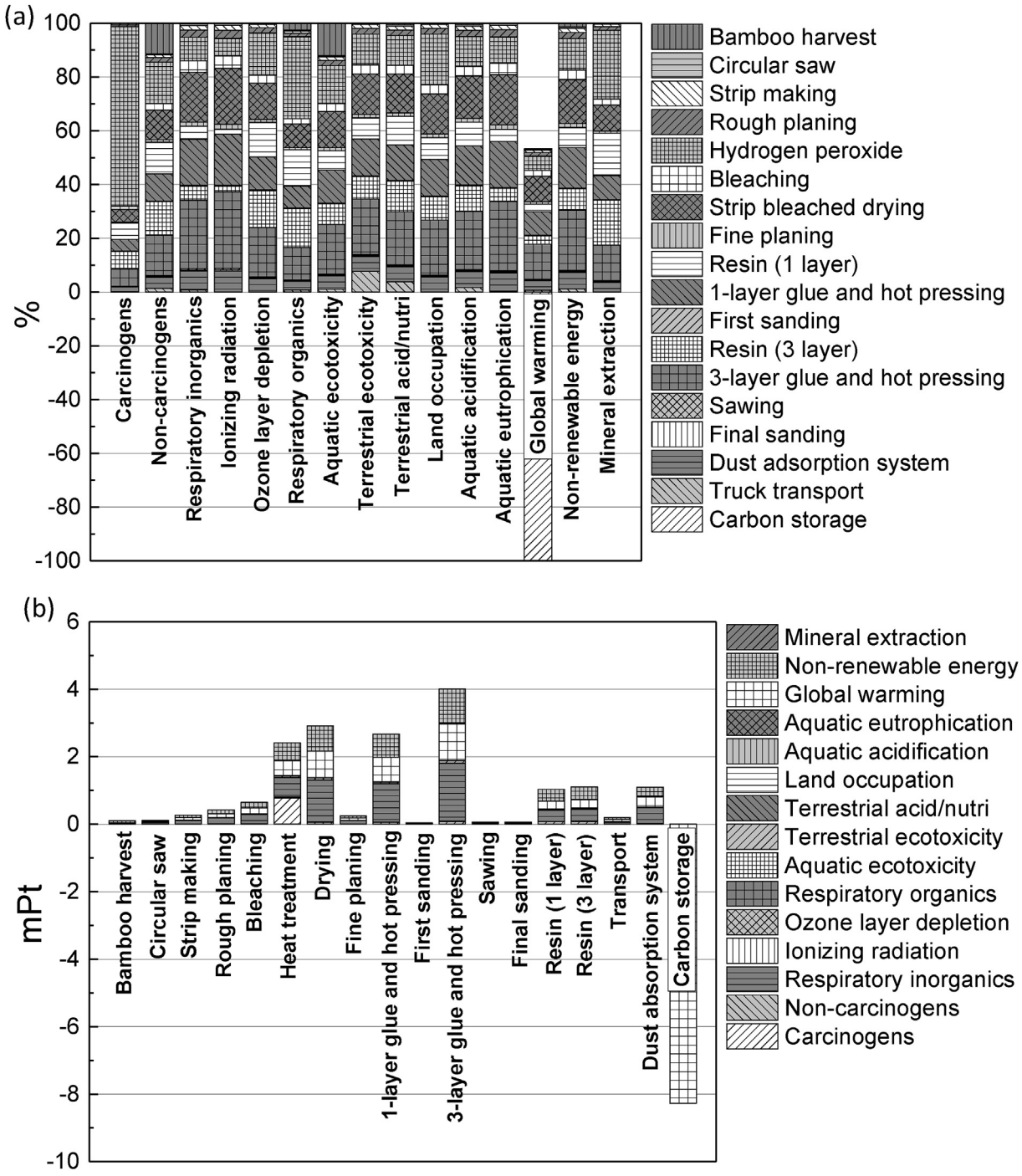

Fig. 2. (a) Characteristics and (b) environmental impacts of bleached glue-laminated bamboo boards.

Table 3
Assessment of the endpoint impact indicator for bleached glue-laminated boards.

Damage category	Unit	Total
Total	mPt	9.06
Human health	mPt	7.98
Ecosystem quality	mPt	4.17×10^{-1}
Climate change	mPt	−3.87
Resources	mPt	4.52

laminated boards, demonstrating that drying exhibits the highest environmental impacts among all processing phases. When bamboo stripes are placed in a high-pressure furnace, steam exceeding 110 °C and appropriate pressure are applied during heat treatment. Under these heating conditions, the bamboo stripes acquire a substantially high moisture content and require a long drying duration, which requires high power consumption. Therefore, the drying process has substantial environmental impacts. However, the carbon storage function of heat-treated glue-laminated boards exhibits a positive environmental effect with regard to global warming.

Fig. 3(b) illustrates the environmental impacts of each processing phase of heat-treated glue-laminated bamboo boards by

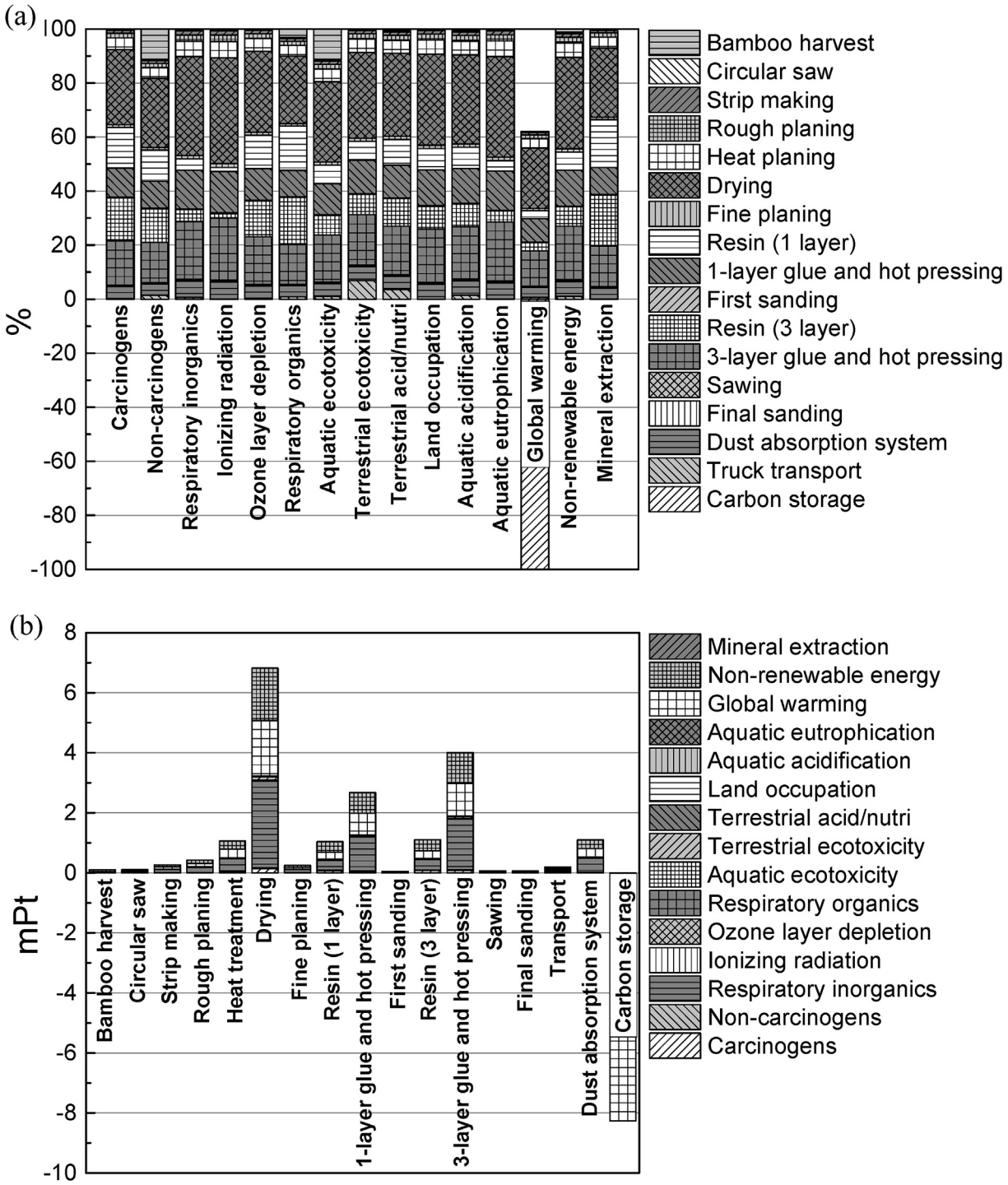

Fig. 3. (a) Characteristics and (b) environmental impact of heat-treated glue-laminated boards.

individual score, demonstrating that the drying and hot pressing phases accumulate a greater environmental impact than any other processing phase. In contrast, with bleached bamboo boards, the heat-treated boards exerted a higher environmental impact during the drying process.

Table 4 lists the assessment results for the endpoint impact indicator of heat-treated glue-laminated boards. This indicator can be used to identify the hazards in each processing phase. The results reveal that similar to their bleached counterparts, the processing of heat-treated plybamboo exhibits considerable environmental impacts regarding hazards such as human health, climate change, and resource depletion, particularly during drying, hot pressing, and the phases involving H_2O_2. In summary, to mitigate the environmental impact induced by the manufacturing process of heat-treated glue-laminated bamboo boards, the hazardous processing phases should be addressed first for improvement.

Fig. 4 compares the endpoint impact indicator values for the two glue-laminated board types. Although the bleaching process requires a substantial amount of chemicals, bleached plybamboo exhibits a lower environmental impact in all four categories

Table 4
Assessment of the endpoint impact indicator for heat-treated glue-laminated boards.

Damage category	Unit	Total
Total	mPt	10.95328
Human health	mPt	8.53976
Ecosystem quality	mPt	0.459462
Climate change	mPt	−3.13993
Resources	mPt	5.093982

because heat-treated plybamboo consumes more power. However, because restructuring the domestic energy structure remains challenging, equipment that consumes less power or enables efficient production is the preferred methods for mitigating the environmental impacts incurred by the production process.

The characterization of various materials demonstrates that bleached, glue-laminated bamboo boards exert the greatest potential environmental impact in terms of power consumption during the three-layer lamination process; in particular, the category with the highest environmental impact is respiratory inorganics, followed by global warming and nonrenewable energy. The result is similar to that of the study of Zea Escamilla and Habert (2014) where 60% of the impact of glue-laminated bamboo could be linked with electricity use. H_2O_2 also exhibits a substantial level of potential environmental impact, particularly on carcinogenic toxicity. For the heat-treated plybamboo, the drying process has a higher potential environmental impact than any other processing phase. Regarding heat-treated bamboo boards, the respiratory inorganics generated from the drying process exert the highest environmental impact, followed by global warming and nonrenewable energy. In addition, glued-laminated bamboo boards comprise biological materials with approximately 50% carbon. Because bamboo materials represent carbon storage in an organic form, the use of bamboo materials exerts a positive environmental effect on global warming. The hazard analysis revealed that the processing phases of glue-laminated bamboo boards exhibit a high environmental impact in the categories of human health, climate change, and depletion of resources, particularly during drying, hot pressing, and the phases involving H_2O_2. The comparison of the two treatment types reveals that the bleached, glue-laminated bamboo boards have a lower environmental impact in all four categories than their heat-treated counterparts.

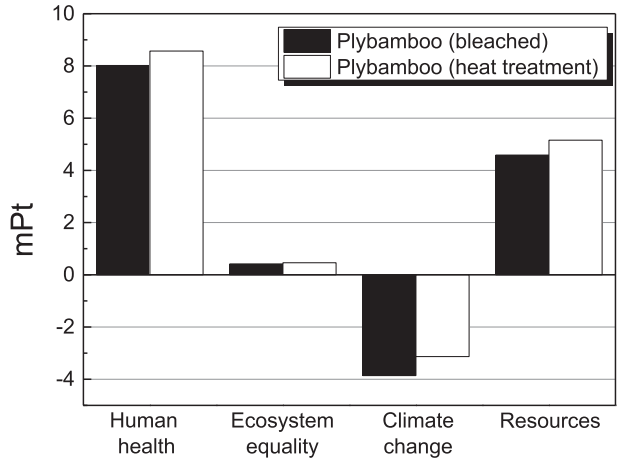

Fig. 4. Comparison of impact indicator values for both glue-laminated board types.

3.3. Comparison of greenhouse gas emissions between glue-laminated bamboo and other materials

Over the past century, human activities have led to the emissions of greenhouse gases (GHG) such as CO_2, resulting in the threats of global warming. The climate change caused by global warming has created substantial ecological and socioeconomic damage worldwide. Therefore, using materials with low carbon emissions or adequate carbon storage functions can mitigate global warming. According to the data compiled by Chang (2002), the present study compared the GHG emissions from the production processes of various building materials in Taiwan.

As shown in Fig. 5(a), the production of glue-laminated bamboo boards released more carbon than did other materials, except for aluminum-based materials. In contrast, with timber, bamboo, as a member of the Poaceae family, has hollow stems; therefore, numerous processing phases are required to obtain flat bamboo materials without an arc. In addition, bamboo materials contain a high level of moisture during the processing phases and thus require an extensive drying process to remove the moisture and enhance the dimensional stability and durability. Consequently, excessive power consumption during processing contributes to substantial carbon emissions.

Comparing the carbon emissions per cubic meter of material (Fig. 5(b)) indicates that the production of steel bars incurs greater carbon emissions than that of aluminum-based materials because steel bars exhibit high density (7900 kg/m^3). The carbon emissions of glue-laminated bamboo boards are only higher than those of timber and concrete. However, similar to timber, glue-laminated bamboo boards comprise biological materials with approximately 50% carbon, and the usage of bamboo materials is equivalent to carbon storage in an organic form. The negative value of the carbon emissions from glue-laminated bamboo boards demonstrates that the carbon storage function of the bamboo material offsets the carbon emissions during the processing phases, resulting in lower gross carbon emissions compared with other materials. Therefore, the use of glue-laminated bamboo boards exerts positive environmental effects.

3.4. Comparison of environmental impacts between glue-laminated bamboo and other materials

This study referred to the Ecoinvest database to compare the environmental impacts of various materials. Fig. 6 illustrates the characteristics of various materials, including the glue-laminated bamboo boards discussed in this study. The results revealed that although concrete scored higher in the global warming category than did glue-laminated bamboo boards, its scores in the remaining categories were lower than those of other materials. Glued-laminated bamboo boards exerted a higher effect of ionizing radiation than did polyvinyl chloride (PVC), but its scores in the remaining categories were lower than those of aluminum-based materials, steel bars, and PVC. This suggests that the power consumption expended for the production of plybamboo generates substantial environmental impacts, particularly because of the multiple steps required for processing bamboo materials and how the Taiwanese energy structure mainly comprises thermal power generation.

Table 5 compares the endpoint impact indicator values between various materials. The results demonstrated that only concrete scored higher in the climate change category than glue-laminated bamboo boards, but its scores in the remaining categories were the lowest. Glue-laminated bamboo boards exhibited a positive environmental effect on global warming hazards because of their carbon storage functions.

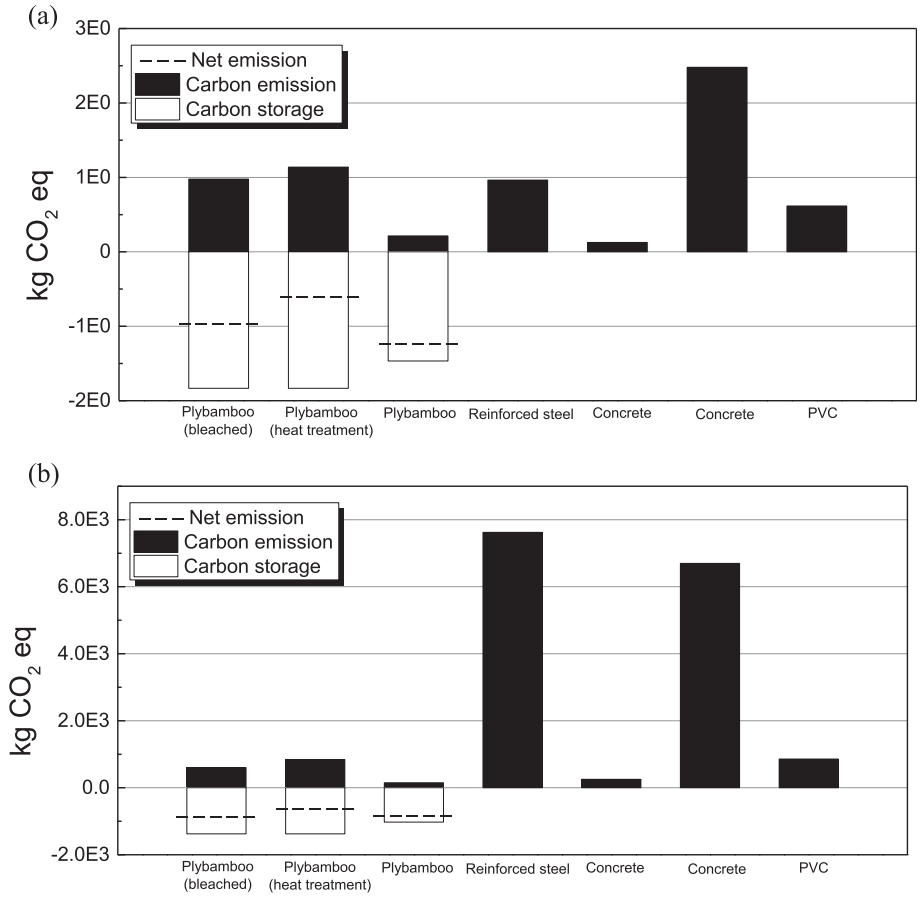

Fig. 5. GHG emissions (a) by material per kilogram and (b) by material per cubic meter.

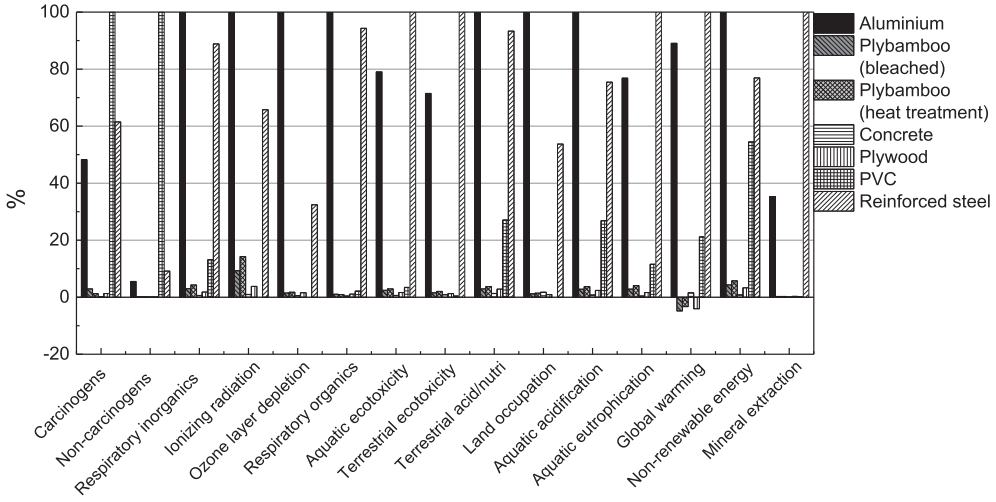

Fig. 6. Characteristics of various materials.

Table 5
Assessment of the endpoint impact indicator for various materials.

Damage category	Aluminium	Plybamboo (bleached)	Plybamboo (heat treatment)	Concrete	Plywood	PVC	Steel
Total	6.78	1.04×10^{-1}	1.81×10^{-1}	6.11×10^{-2}	5.51×10^{-2}	5.28	6.57
Human health	3.57	1.13×10^{-1}	1.42×10^{-1}	2.10×10^{-2}	6.64×10^{-2}	4.12	3.42
Ecosystem quality	2.65×10^{-1}	5.58×10^{-3}	7.25×10^{-3}	3.44×10^{-3}	4.64×10^{-3}	7.07×10^{-3}	3.33×10^{-1}
Climate change	1.44	-7.81×10^{-2}	-5.37×10^{-2}	2.48×10^{-2}	-6.51×10^{-2}	3.42×10^{-1}	1.62
Resources	1.51	6.36×10^{-2}	8.47×10^{-2}	1.19×10^{-2}	4.91×10^{-2}	8.10×10^{-1}	1.20

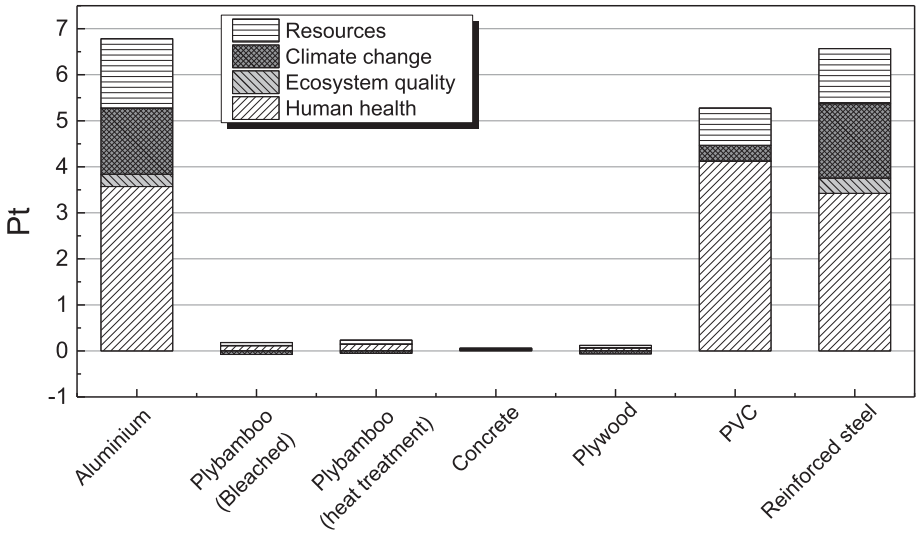

Fig. 7. Environmental impacts of various materials by individual score.

Fig. 7 illustrates the aggregated scores of the hazards of various materials. The results show that aluminum-based materials exerted the highest environmental impact among the materials listed. Although glue-laminated bamboo boards attained a higher score for the overall environmental impact than concrete, in practice using concrete as a building material still requires the support of steel bars (Wang and Tu, 2007) and thus greatly increases its environmental effect. In addition, bamboo is considered a renewable material. If the productivity and power consumption during the processing phases can be addressed, glue-laminated bamboo boards have tremendous potential as an environmentally friendly material. Therefore, policy makers should consider the highest impact of the above-mentioned processing step, and use energy-saving and high productivity equipments to reduce the environmental impact.

4. Conclusion

This paper presents the potential environmental impacts/benefits and the carbon storage of the plybamboo industry in Taiwan through a life cycle assessment (LCA). The unit processes include harvesting, preprocessing, H_2O_2 treatment, bleaching, hot pressing, sawing, and transportation. Site information was reported on the environmental impacts, the endpoint impact indicator values, and the carbon emissions of the overall system compared with other materials. The life cycle inventory analysis revealed that the production of bamboo materials is mainly conducted by mechanical processing and that both power consumption and productivity are key potential environmental influences in the LCA. Therefore, the energy structure in Taiwan is the leading factor affecting environmental pollution during the production of bamboo materials. The comparison with other materials yielded the following results. Concrete had a lower environmental impact than any other material, but it scored higher in the global warming category than the glue-laminated bamboo boards did, whereas glue-laminated bamboo boards had lower environmental impacts than aluminum-based materials, steel bars, and PVC, despite scoring higher in the ionizing radiation category than PVC. Concrete generated the lowest hazard among the listed materials, but it scored higher in the global warming category than the glued-laminated bamboo boards, which had a positive environmental effect on global warming hazards; aluminum-based materials generated the most hazards among the listed materials. Although the glue-laminated bamboo boards had higher GHG emissions than concrete, the carbon storage functions offset the carbon emissions during the processing phases. Therefore, glue-laminated bamboo boards exhibit a positive effect on reducing GHG emissions.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2018.08.248.

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